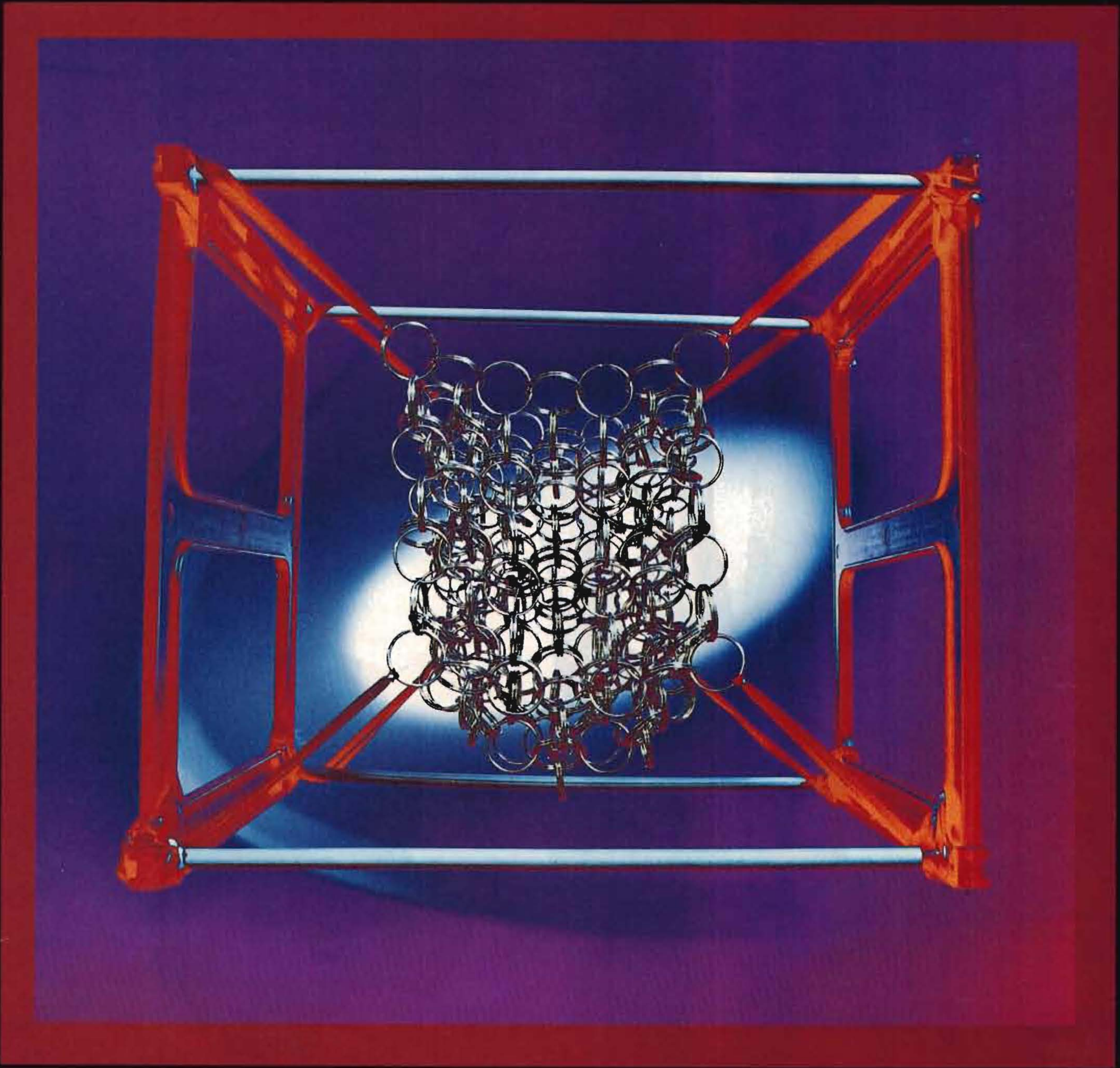
LOOPS



OF SPACE

By Marcia Bartusiak

PHOTOGRAPHS BY JOSEF ASTOR

EVEN EINSTEIN FAILED TO UNITE GRAVITY WITH SUBATOMIC FORCES. NOW IT TURNS OUT THAT BOTH MAY ARISE FROM A FINE MESH OF SPACE-TIME LOOPS.

For all his accomplishments, Einstein never lived to see his fondest dream come true. Our century's best-known physicist spent most of his life searching for a comprehensive set of laws that would explain the behavior of nature on all levels, from quasar to quark. He had, in his twenties, already shown that space and time were intertwined. He then succeeded in showing how gravity is intimately related to the geometry of this curved space-time. But he failed when he tried to weave all aspects of nature—all its forces and fundamental rules—into one seamless cloth. The new science of quantum mechanics simply wouldn't fit, no matter how hard he, or anyone else, tried. ■ Today physicists are still stuck in the same quagmire. Nature seems to play by two sets of rules, and they are incompatible. It's as if physicists were being asked to go bowling with tiddlywinks or to jump-start a car with an eggbeater. The tools that work so well in one realm are totally inappropriate in another. Not only can't they win at this game, they can't even begin to play. ■ Einstein's theory of gravity—also known as general relativity—still describes the universe on its grandest scale with a power that continues to astound physicists. The structure and dynamics of stars, galaxies, black holes, the very shape and evolution of the universe—all are explored using the tools Einstein developed. Gravity, according to this theory, is not the result of invisible tendrils of attraction emanating from a mass, keeping planet to sun or boulder to Earth. Rather, gravity is the result of warps in space-time. Massive objects indent the flexible backdrop of space-time like boulders sitting on a rubber mat. The wells they create naturally attract and frequently "capture" nearby objects, just as potholes attract cars. The language of general relativity speaks of a gently curving space-time, a landscape of hills and basins, a continuous flow of smooth, connected forms. The alphabet of this language is geometry; its vocabulary consists of lines, angles, surfaces, curves. ■ Zoom in on matters subatomic, however, and the landscape suddenly changes. Einstein's rules no longer apply. Atoms and nuclear particles buzz around like angry bees. Their energy and motion are served up in discrete bits, jumpy and blurred, their exact behavior and position forever uncertain. The words *always* and *never*, used so readily in describing the physics of our everyday world, are replaced with the terms *usually* and *seldom*. The language that describes this lumpy landscape is quantum mechanics. Keeping track of such a mad gambol of particles requires a vocabulary that deals with statistical relationships, the probabilities of events. Its alphabet is algebraic symbols and quantum numbers: 1, 1/2, 2. ■ Trying to do general relativity with the rules of quantum mechanics (or vice versa) would be like using the formula for the area of a circle to compute your chances of winning the lottery, or employing probability theory to measure the area of a house. Yet physicists find themselves in just such a position. They can't proceed until they find a common vocabulary that will enable the quantum theorist to talk freely with the relativist, allowing the lumpy microcosm to join with the smooth macrocosm in an all-embracing theory of "quantum gravity." In fact, given such strikingly different pictures of reality, it's somewhat surprising that physics has been able to progress at all. ■ Certainly a theory of quantum gravity is not needed to help us understand events in our everyday world, such as the flight of a rocket or the path of a bowling ball rolling down an alley. Current laws of physics are quite sufficient to handle those types of problems. Applying laws any more precise would be wasteful, as if you were to use an atomic clock to get you to the airport on time. But quantum gravity is required in any situation where extreme subtleties are involved, or where gravity is concentrated and the

Model courtesy Carlo Rovelli

Physicist Carlo Rovelli jokes that he used "every available key ring in Verona" to create this stunning metal mesh—a three-dimensional model of quantum loop space.

effects of errors are vastly multiplied. Such situations include some of science's most vexing mysteries.

It's well established, for example, that gravity controls the motions of stars and galaxies, but what does gravity do when all the matter in a star is squeezed tighter and tighter, until the size of the star becomes atomic rather than celestial? That squeezing may be what happens when a particularly massive star explodes as a supernova and, within a wink, its remnant core collapses into a black hole, that gravitational abyss from which no light or matter can escape. What lies at the heart of this black hole? Einstein's theory of general relativity "blows up" when it attempts to describe its inner recesses. The calculations go awry. The only thing that theorists get for their trouble is a basketful of infinities.

RELATIVISTS ARGUED THAT THE JOB HAD TO BE DONE BY ALLOWING THE GEOMETRY OF SPACE-TIME TO BECOME AN ACTIVE PLAYER INSTEAD OF MERELY A PASSIVE STAGE.

And what if we could turn back the cosmic clock some 15 billion years, to the time of the Big Bang, when all the matter and energy in the visible universe was tucked away in a space no bigger than a subatomic speck. How did gravity act under those hellishly confined conditions? And how did such behavior produce the universe we presently see around us? No one can yet say. A complete understanding of gravity's behavior on subatomic scales will not arrive until physicists can merge general relativity with quantum mechanics and thus fashion a successful theory of quantum gravity.

That is why the work of Syracuse University physicists Abhay Ashtekar and Lee Smolin, and their colleague Carlo Rovelli of the University of Pittsburgh and the University of Trento in Italy, is creating a bit of a stir within the physics community. Over the last few years these three men have been carrying out a series of calculations that could be moving physics many steps closer to its cherished goal, finding a path through the mathematical roadblocks that have frustrated theorists for decades in their pursuit of quantum gravity. And what is emerging from their initial explorations is a tantalizing picture of what space might look like on the tiniest levels. Instead of a space-time that's immeasurably smooth, their calculations hint that it might have a fine-grained structure, a texture that resembles a carpet woven out of an endless series of ultrasmall loops, interlinked in every direction. For years physicists and science writers alike have spoken of the "fabric" of space-time; incredibly enough, they might literally be right.

The need for a theory of quantum gravity is so compelling that some of the most imaginative, stubborn, and celebrated physicists in twentieth-century science have worked on the problem at one time or another. Serious work began in the late 1940s, right after the war. And the most popular tactic in the attempts to merge gravity with quantum mechanics was to view gravity much like the other forces that already fit nicely into the quantum fold—namely, electromagnetism and the strong and weak nuclear forces.

Everything in the quantum mechanical universe—energy, motion, spin, and so forth—comes in indivisible bits. Forces fit naturally into this framework. Instead of viewing magnetism, say, as the result of invisible lines of force emanating from a magnet, the quantum world transforms the notion of force into an exchange of force particles—a subatomic tennis game. In electromagnetism this diminutive tennis ball is the photon, a particle that constantly bounces between charged particles, generating a force of either attraction or repulsion. In the same way, gravity is conveyed among masses by the continual transmission and absorption of gravitons, particles that exist, for now, only hypothetically; they have not been detected.

Mathematically, physicists treated these particles as tiny excitations, or "perturbations"—small waves moving about the large, calm ocean of space. But when it came to quantum gravity, a major problem arose: theories that treat forces as particles assume that every event in the subatomic world takes place on a fixed, unchanging background of space and time. Space-time is the stage upon which the actors, particles such as photons and gravitons, flit to and fro. "Take light, for example," says Ashtekar. "We imagine that space and time are just sitting here. Turn on a switch, and the light comes. Turn off the switch, and the light disappears. Space-time is not a participant."

But in general relativity the distinction between stage and actor doesn't exist. Physicists were saying that the force of gravity arises whenever particles are exchanged. But according to Einstein, gravity was the very geometry of space-time. Thus the graviton became both actor and stage simultaneously. A graviton could enter onto the stage of space-time, but by doing so it ended up bending and warping the stage as if it were so much Jell-O. This dual role made gravity nearly impossible to handle with the mathematical techniques that the physicists were using for other forces. When they tried, their results made no sense whatsoever; the odds of a certain event's occurring, for example, could turn out to be greater than 100 percent.

General relativists recognized this problem early on and argued with particle theorists that the job had to be done in a different way altogether, one that allowed for the geometry of space-time to become an active player instead of merely a passive stage. A proper theory of quantum gravity, they said, should allow space to evolve and change in response to forces or the presence of mass. Oxford mathematician Roger Penrose chastised the particle physicists for attempting to "steamroll general relativity flat and then wave the magic wand of quantum theory over the resulting

Syracuse physicists Lee Smolin (left) and
Abhay Ashtekar (center) teamed up with Carlo Rovelli of the University of Pittsburgh and the University of Trento
in Italy to rewrite Einstein's equations.

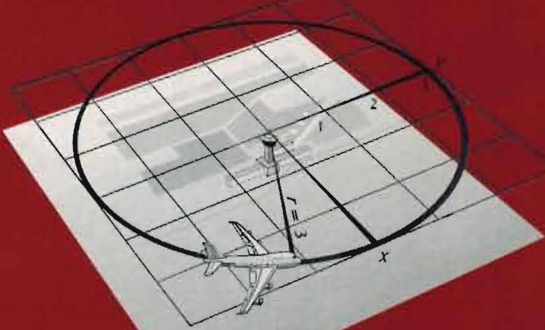
corpse." Gravity could simply not be handled like the other forces; it was different. Rallying behind Penrose, relativists returned to the classical theory of general relativity itself and worked on putting the equations into a form that could be treated by quantum mechanics directly, but without necessarily assuming that gravity has to boil down ultimately to an exchange of particles. Unfortunately, upon setting up their own equations, they found them absolutely impossible to solve, as if they had erected a beautiful house without any doors through which to enter.

Mathematicians, like other tinkerers, need tools to pry open the meaning of their equations. Let's say you have an equation—for example, $x^2 = 4$. To find out what x is, you take the square root of 4. The same approach works for any value of x, but if you didn't know about square roots—if you didn't have the tool—you wouldn't be able to solve the equation. The relativists had set up equations that amounted to elegant statements about how gravity would behave under quantum conditions. They were internally consistent. The grammar was right. They made sense. The only problem was that the physicists didn't have the mathematical tools to generate solutions.

Relativists might have been stymied for decades had it not been for a breakthrough in 1985 that changed the way in which they thought about quantum gravity. That year Ashtekar, a relativist, erected the first crossable bridge between general relativity and quantum mechanics. It is a bridge that he had wanted to build ever since college.

SHIFTING FRAMES OF REFERENCE

If you want to use the familiar x and y grid to describe the path of an airplane circling a control tower at a distance of three miles, you need to use the equation $x^2 + y^2 = 3^2$. If you know the x coordinate (say, latitude), you can always figure out the y coordinate (say, longitude), but it's rather messy. On the other hand, imagine that you erase the grid and simply think of radial lines emanating from the central point, or control tower. Now the equation that gives the plane's path is simply $r = 3$. This is so simple it may seem obvious. But the simplicity results from viewing the problem in a new coordinate system.



IAN WORPOLE

Ashtekar was born in 1949 in the small town of Shirpur near India's west coast; he was drawn to physics through the popular books of cosmologist George Gamow. That he had a flair for physics was apparent soon after he entered the University of Bombay. Finding a mistake in a classic text written by Nobel laureate Richard Feynman, he boldly wrote the great physicist to inform him of the error. "Feynman actually replied and agreed the book was wrong. It was so uplifting that I still have the letter," says Ashtekar.

Ashtekar's interest in cosmology naturally led to his study of general relativity, because it is through Einstein's equations that cosmologists can understand how the universe expands and why it looks the way it does. By the time he arrived in the United States in 1969 to pursue his graduate degree, he already knew that the field of relativity, far removed from the public spotlight, best suited his reflective personality and mathematical inclinations. "Relativity has the reputation of being a 'gentlemanly' pursuit," he says with a smile. "You can freely talk with your colleagues and never worry about someone stealing your results," a situation in stark contrast to the more rough-and-tumble atmosphere of high-energy particle physics.

Quantum gravity was a particular attraction. "There's a sort of innocent arrogance when you're young," Ashtekar says, "encouraging you to tackle the most difficult problems." He struggled with it throughout the 1970s, as he graduated from the University of Chicago and moved on to a series of professional appointments. But quantum gravity eluded him, just as it had his fellow relativists.

What was missing, he suspected, was one key idea, perhaps something on the same level as the insights that led to the development of quantum mechanics. Before 1900, physicists were perplexed by the confusing experimental data on the way light was absorbed and emitted. Then German physicist Max Planck proposed that energy did not flow continuously in an unbroken stream but came instead in discrete packets, or "quanta" (from Latin, meaning "how much"). Indeed, when light was thought of as a barrage of particles, called photons, the experiments suddenly made sense. Planck derived a quantity—known as Planck's constant—to describe the minimum amount of energy possible in the quantum universe, the finest possible grain.

Ashtekar's insight came in the form of a mathematical breakthrough rather than a novel physical idea. His new approach arrived by way of a University of Chicago graduate student named Amitabha Sen, now a physicist with Motorola in Washington, D.C. What Sen developed was a way of dealing with geometric curvatures that allowed him to describe better the motion of an electron caught within a gravitational field. "I had an intuition about Sen's approach, that it would be extremely valuable in general relativity," recalls Ashtekar.

He was right. Inspired by Sen's work, Ashtekar was able to introduce two new mathematical functions, or relationships—in effect, a novel geometric language in which to rewrite Einstein's theory of general relativity. As Ashtekar well knew, physical insights often depend on the proper choice of mathematics. Newton's laws dealing with the motions of the planets depended critically on a new kind of mathematics—calculus—that could describe forces and objects in a state of constant change. Einstein, in turn, might never have connected gravity to curved space-time if he hadn't come across Riemannian geometry, the geometry of curved surfaces.

To see how the proper mathematics can make a complex problem simpler, imagine an everyday problem: Take an airplane circling an airport from three miles away. If you want to describe its motion using the geometry of a flat grid, the result is very messy. Every time the plane changes position, its longitude and latitude change, too. If you designate its east-west position x, and its north-south position y, then the equation that describes its route is $x^2 + y^2 = 3^2$. The coordinates are constantly changing. But let's say you shift to a different geometry: a graph with radial, or circular, coordinates. In that case you don't have to worry about x's and y's at all. The plane is simply three miles from the center of a circle, and the equation that describes its flight path is no more complicated than $r = 3$ (radius = 3).

> WITH REAMS OF PAPER SPREAD OUT OVER THE KITCHEN TABLE, THEY FOUND SOLUTION AFTER SOLUTION FOR EQUATIONS THOUGHT IMPOSSIBLE TO SOLVE.

In a sense, Ashtekar found a way of rewriting Einstein's equations using new mathematical variables. It was a task that required several years of contemplation and blind alleys, followed by weeks of filling up his office blackboard with new equations. However, it was worth the wait. Transformed by Ashtekar, Einstein's equations came to strongly resemble equations already easily handled in quantum mechanics. Indeed, the quartet of equations that Ashtekar derived were similar in many respects to equations introduced by James Clerk Maxwell more than a century ago that showed electricity and magnetism to be just two different aspects of the same force. Electromagnetism had been the first force that physicists successfully merged with the quantum world; with general relativity now looking more like electromagnetism, the union with quantum mechanics appeared more promising than ever.

In the abstract and frequently arcane world of quantum gravity, Ashtekar's name is now regularly invoked. Papers in the *Journal of Classical and Quantum Gravity*, a bible in the field, regularly refer to "Ashtekar's theory of gravity," "the Ashtekar formulation of general relativity," and "Ashtekar's variables."

The mathematics itself is not a new invention; similar kinds of tools have already been used in other areas of physics. Technically, mathematicians refer to the two tools that Ashtekar introduced as a "connection" and a "frame field." A connection (the more important of the two) is a way of defining the geometry of an object—how the surface of a sphere or saddle curves, for instance—a valuable commodity when dealing with curving warps in space-time. Just as the equation $x^2 + y^2 = 3^2$ described our circle, so more-complicated equations describe more-complex kinds of curves. A connection is a clever mathematical device that allows you more easily to map and measure curvatures, including the curvatures of space-time. Even Einstein stumbled when he tried to rewrite general relativity in terms of connections. Ashtekar's great accomplishment was finding a unique pair of mathematical forms that got the job done.

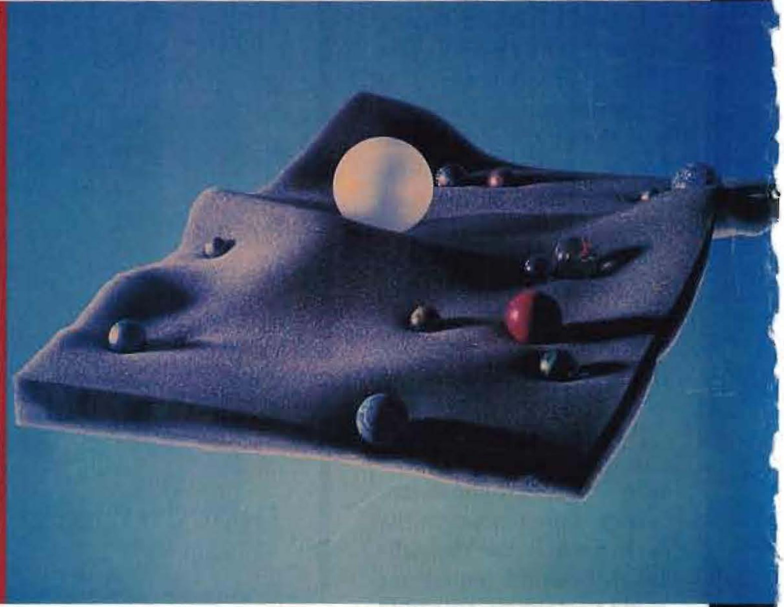
Oddly enough, there were no shouts of "Eureka!" when Ashtekar published his results in 1986. More attention was then being paid to the new (and far more popular) kid on the block, "superstrings." Superstrings is more than a theory of quantum gravity, the straightforward union of general relativity with quantum mechanics. It is, at the same time, an all-encompassing "theory of everything." In other words, it attempts to show how gravity and all the other forces are just different manifestations of one ancestral force—a unified force—that briefly existed at the dawn of time. Over the last few years, however, superstring theory has fallen on hard times. Not only is its mathematics intractable, but there doesn't seem to be a unique superstring solution that applies to our universe alone. "There are *zillions* of string theories!" exclaims Smolin.

Consequently, Ashtekar's approach began to look more attractive—and more doable. It isn't a theory of everything, describing all the forces by one law. It's simply a means of examining how gravity might act as you examine smaller and smaller slices of space, until you enter the lilliputian territory ruled by quantum mechanics.

In early 1986, before his new form of general relativity was officially published, Ashtekar presented a series of lectures on the idea at a quantum gravity workshop held at the Institute for Theoretical Physics, located at the University of California at Santa Barbara. Lee Smolin, a young and enthusiastic investigator in the field, was in the audience.

Ten years earlier, when Smolin had arrived at Harvard to work on his graduate degree, he'd gone against the advice of all his professors to pursue quantum gravity, a subject then considered far from the paths of glory in physics. As Smolin puts it, "You didn't know if you were 5 years, 50 years, or 100 years from an answer." The Santa Barbara meeting was a turning point for him. After Ashtekar described his reformation of general relativity, Smolin and another young relativist at the workshop, Ted Jacobson, now with the University of Maryland, immediately teamed up to clear a path to possible solutions. They didn't think they could actually solve Einstein's equations using Ashtekar's new framework, but, almost accidentally, they did. Jacobson remembers sitting in his kitchen with Smolin, reams of paper spread out over the table, finding solution after solution for equations once deemed impossible to solve. They were carrying out the first, tentative translations in the new quantum language.

Interest in the method spread, swiftly generating converts, the most important of whom was Carlo Rovelli of Verona. Rovelli had been attracted to science relatively late, not until the age of 20, after participating in Italy's student rebellions in the early 1970s. "We lost the revolution, so I decided to try physics," he says. While working as a postdoc in 1986, he wangled an Italian fellowship (and funds from his father) for travel to the United States to work specifically with Ashtekar and Smolin. Affable, creative, and easygoing, Rovelli quickly settled into the role of go-between, helping mesh the analytic powers of the quiet, contemplative Ashtekar with the creativity of the brash, impetuous Smolin.



A MARRIAGE MADE IN LOOP SPACE

The curving landscape of Einstein's general relativity (near right) seems incompatible with the blurred and choppy universe of quantum mechanics (far right). But what if the fine-grained structure of space-time turns out to be a carpet woven of ultrasmall loops (center)? Then the two disparate worlds might be reconciled at last.

Imagine Johann Sebastian Bach joining forces with Thelonious Monk. As physicists, Ashtekar and Smolin present a similar contrast. Ashtekar's attention to detail and form is reflected in his Syracuse office. The room is a scientific monastery. There are no stray papers in sight; tape dispenser, stapler, and pencil holder line up in regimental order on the desk. Only a single poster graces the far wall, a portrait of Wolfgang Amadeus Mozart. "A man ahead of his time," remarks Ashtekar.

Just three doors down from Ashtekar's office, another room appears as if it had been caught in the calamitous path of Hurricane Andrew. Books, clothes, and journals litter the floor and every available surface. "I don't really use this room much as an office, more like a closet," says Smolin sheepishly, running a hand through his unruly hair. Like the subatomic particles that he studies, Smolin is never at rest. You catch him on the run.

With the arrival of Rovelli, the disparate twosome turned into a more balanced triumvirate. If Ashtekar is the baroque composer and Smolin the jazz musician, more impulsive and experimental, then Rovelli is someone like trumpeter Wynton Marsalis, who is equally at home playing either jazz or the classics. "The way each of us organizes our thoughts is incredibly different, which can be frustrating," says Rovelli. "Yet we understand together what we couldn't understand separately."

Like advance scouts exploring a new territory, Rovelli and Smolin began to plumb Ashtekar's equations ever more deeply, figuring out what they might be able to say about space and time. Smolin had earlier noticed that the solutions he was finding shared an uncanny resemblance to solutions to classic mathematical problems involving knots. Smolin explored this relationship in vain for a year, and he explained it to Rovelli when he arrived. Within a day Rovelli was able to respond: "I know how to do it."

Rovelli proposed a new technique that used loops—which are closely related to knots—as a basis for quantum theory. Combining the Ashtekar equations with the loop technique spawned a new set of equations in which each seemed to represent a possible configuration of space-time. And if the mathematics looked similar, that was a broad hint that the physical reality might be similar, too. The solutions that worked best described simple open loops, linked together. Realizing this, Rovelli and Smolin came to confront what other quantum theorists had suspected for decades: that our everyday notions about space may have to be altered. "What we found exceeded our wildest expectations," says Smolin.

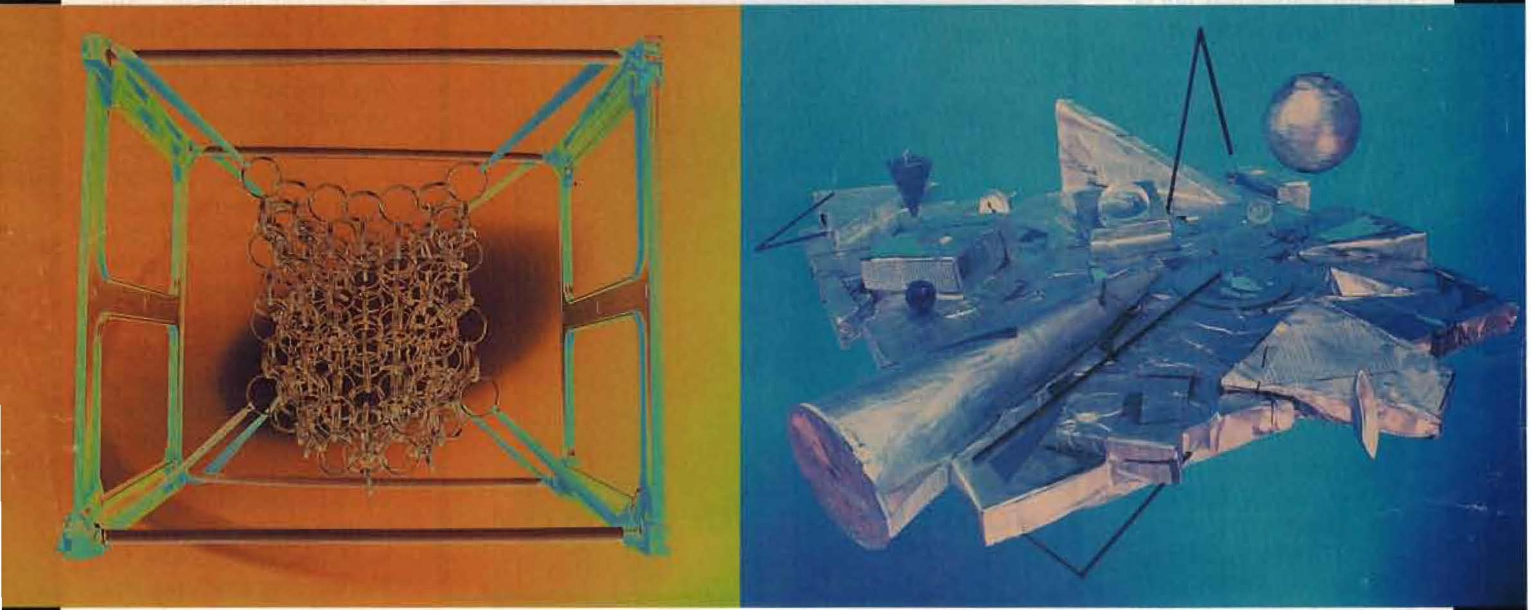
It's natural to think of space as a continuous and uniform medium. Swing your arm through the air and the motion proceeds freely and fluidly from one point in space to the next. But that sense of space as a smooth continuum could be merely an illusion. Rovelli and Smolin believe that space, at the very tiniest of sub-submicroscopic levels, is actually constructed out of loops, separate and discrete units.

That space might have a texture is not an entirely new idea. In the 1950s Princeton theorist John Archibald Wheeler, now the doyen of relativity in the United States (he coined the term *black hole*), suggested that space might consist of a sort of "space-time foam," a froth of space-time bubbles. "But the space-time foam was based on a simple estimate," explains Wheeler. "What Ashtekar, Smolin, and Rovelli have done is spell out the mathematics of that foam." By applying the loop formulation of quantum theory to the problem,

MODELS BY FAITH MEADE AND CHARLIE WELCH

they were the first to derive discrete units of space directly from the equations of general relativity.

Once you get adjusted to the notion of spatial building blocks, it seems quite natural; it's what quantum mechanics is all about. A slab of iron, for example, looks quite solid and uniform to our eyes, but when examined down to a billionth of a centimeter, it is nothing more than empty space peppered with distinct particles, such as protons and neutrons. These, in turn, can be further subdivided into quarks. Now space joins the quantum party, but only at an amazingly small scale; the diameter of a quantum loop is a minuscule 10^{-33} centimeter (a million-billion-billion-billionths of a centimeter). And that number, in turn, is a measure of the Planck length—the minimum grain size conceivable in our universe, derived from the minimum unit of energy.



If an atom were blown up to the size of our galaxy, which spans some 100,000 light-years, one of these quantum loops would still be no bigger than a human cell. "So it's not surprising that space looks so smooth, just as a T-shirt seen from a distance looks smooth," says Rovelli. If matter were squeezed to such a tiny dimension, gravity—usually the weakest of nature's forces—would overwhelm all the other forces. Yet nothing will ever be known about that fateful transition until a theory of quantum gravity is successfully forged.

And what is a quantum loop? In many ways it resembles the lines of magnetic force surrounding a bar magnet, the halo of lines that is so apparent when you sprinkle iron filings around the bar. Each loop, in fact, can be thought of as the gravitational equivalent of a magnetic line of force—a gravitational excitation. Nothing exists inside or outside a loop line, not even empty space; the loop itself *defines* space.

According to Smolin, it is difficult to talk about the properties of one loop of space, just as you can't talk about the temperature or density of a single atom. Temperature and density become meaningful only when you're dealing with trillions and trillions of atoms. Similarly, the space so familiar to us emerges only when considering countless numbers of loops, all interconnecting for inches, miles, and light-years on end. Einstein had described space-time as a smooth mat, but the concept of quantum loops suggests that it's more like a net—a net with the finest of meshes.

That's exactly what Ashtekar, Rovelli, and Smolin described in a paper entitled "Weaving a Classical Geometry with Quantum Threads." If there were a microscope powerful enough to examine quantum space, they informed us, we would begin to perceive it as a never-ending carpet, spreading outward in every direction. At first the loop-space team thought this carpet might be constructed like a textile, with infinitely long threads interwoven to form the fabric of space-time. A quantum loop would then be the smallest cell in this weave. Ashtekar even took a weaving lesson to gain more insight into this imagery. But the three researchers eventually concluded that the carpet's construction would more resemble chain mail, the flexible armor worn by medieval soldiers. Each loop of the carpet would be separate and distinct, yet linked to its neighbors. To get a better idea of how this works, Rovelli built a three-dimensional model, a stunning mesh of metal circles, using hundreds of key rings—"every available key ring in Verona," he jokes.

Given this fabric, it becomes possible to think how the weave can be used. Gravity, for instance, might be the result of a bit of embroidery on the weave; you might imagine a graviton as a single loop of embroidery stitched into the net. A large collection of gravitons would distort the weave, just as mass distorts space-time. More intricate knots or distortions in the quantum threads might represent other types of physical effects, although that is extremely speculative at the moment. And the long-held suspicion in physics that nothing can be smaller than the Planck length starts to make sense when picturing the quantum loops; if a particle were smaller than a loop, there would be no scaffolding on which to "hang" it. Space-time simply doesn't exist where loop lines are absent, any more than a blanket exists between the weave of its threads.

Since Ashtekar first published his groundbreaking paper seven years ago, dozens of theorists have written more than 200 papers dissecting, amending, and extending the topic. Researchers from around the globe—from Sweden, England, India, Japan, Germany, South America—arrive monthly at Syracuse and Pittsburgh to learn from the loop-space gurus. "Once I read Ashtekar's paper, I couldn't think of gravity in any other way. I'm surprised it wasn't done earlier," says Jerzy Lewandowski, a Fulbright scholar now at the University of Florida.

That's not to say that everyone is greeting the new development with open arms. Both general relativists and quantum theorists alike have some serious concerns about quantum loops. Ted Jacobson, who had so eagerly embraced Ashtekar's approach at first, now suspects that the solutions he worked on with Smolin may not be physically significant, more a mathematical trick than a peek at reality. Just because equations don't lead to nonsensical results doesn't mean they lead to physically correct results, either. "For the moment, the Syracuse and Pittsburgh researchers seem to be driven more by intuition and hope," he cautions. "I don't believe their mathematics yet supports the conclusion that the loops correspond to discrete space."

> A FULL-BLOWN THEORY OF QUANTUM GRAVITY COULD MAKE OUR CURRENT IDEAS ABOUT THE BIG BANG LOOK AS QUAINT AS PTOLEMY'S EARTH-CENTERED MODEL OF THE SOLAR SYSTEM.

Ashtekar agrees that the status of this new field is far from settled. And yet he argues: "If a new variable appreciably simplifies a problem in physics, it's often telling us something very deep, that nature is really built out of those variables."

Others are more wary of the science. They acknowledge that the mathematics of loop space is beautiful but wonder when some full-fledged physics is going to get done. "They have to tie their method to something that could, at least in theory with some sort of thought experiment, be observed in the real world," says Bryce DeWitt, a quantum theorist with the University of Texas at Austin and one of the founding fathers of the field of quantum gravity. "Only then will we know whether this approach is useful to pursue."

Ashtekar, Rovelli, and Smolin believe such criticism is fair but stress that they are far from formulating a complete theory of quantum gravity. "It's uncharted territory," points out Ashtekar. "Conceptual revolutions don't happen quickly." In fact, to simplify their initial calculations, Ashtekar and his colleagues have been working in a timeless space, a space without a clock. Before they can start making predictions about how the space-time fabric might behave at the quantum level (predictions being the engine that drives science forward), they must figure out a way to bring time back into their equations. They need a quantum clock. And that may require some new mathematics, one of the reasons Ashtekar and Smolin are moving to Penn State next fall. "The Penn State mathematics department has experts in knot theory, complex analysis, and operator algebras, all areas important to our work," says Ashtekar. The university lured him with the offer to establish a research center in general relativity and quantum gravity.

The desire to crack the problem of quantum gravity is certainly seductive, although the theory can never be tested directly; to reach the temperatures and pressures at which the law of quantum gravity kicks in, physicists would have to duplicate the conditions of the Big Bang, a technological feat not expected anytime soon. "The best we can hope to do are indirect tests," says Ashtekar, "figuring out how the quantum-mechanical weave state would manifest itself in our everyday physics. It's a tall order, but possible in the coming years."

Still, there are already hints that a viable theory of quantum gravity could lead to some interesting insights. Nearly 20 years ago Stephen Hawking startled the astronomical community by announcing that black holes "ain't so black." According to the Cambridge physicist, black holes—those bottomless gravity wells from which nothing can supposedly ever escape—slowly emit radiation and actually evaporate away. No one ever expected black holes to behave in this crazy way, but that seems to be the conclusion when quantum rules are applied to the strongest gravitational field that nature can offer. "It tells us something deep about how the world is put together," notes Smolin. Black hole evaporation is a hint of the sort of surprises in store for physicists when a full-blown theory of quantum gravity is at last achieved. Might it drastically change our view of the universe? "Absolutely," answers Smolin. "Our current theory of the Big Bang may look as quaint as Ptolemy's Earth-centered model of the solar system."

The loop-space investigators are generating a lot of press these days, but other schemes for quantum gravity are being actively pursued as well. Roger Penrose has offered an idea whereby the continuum of space-time is somehow built up from more fundamental processes that involve particles with spin. He calls it his twistor theory. Others, such as Hawking, are looking for answers by applying the laws of quantum mechanics to the universe at large, in hopes of recreating the time in our cosmic history, many eons ago, when quantum gravity reigned supreme. And superstring theory is still the richest, if most complicated, candidate around.

Of course, the possibility remains that none of these approaches will pan out. Maybe physicists will again have to experience a change in their basic understanding of the physical world as revolutionary and startling as the shift from classical to quantum mechanics.

Smolin himself confesses that he leans toward this view. "I'm surprised that the loop-space theory has gone this far, because I've always strongly believed that almost anything we now invent, educated as we are in a mostly classical framework, is unlikely to be radical enough."